ELSEVIER

Atmospheric Environment 38 (2004) 405–413

ATMOSPHERIC ENVIRONMENT

www.elsevier.com/locate/atmosenv

Effect of central fans and in-duct filters on deposition rates of ultrafine and fine particles in an occupied townhouse

Lance A. Wallace[a,*], Steven J. Emmerich[b], Cynthia Howard-Reed[b]

[a] *US Environmental Protection Agency, 11568 Woodhollow Court, Reston VA 20191, USA*

[b] *National Institute of Standards and Technology, Gaithersburg MD 20899, USA*

Received 10 August 2003; accepted 3 October 2003

Abstract

Airborne particles are implicated in morbidity and mortality of certain high-risk subpopulations. Exposure to particles occurs mostly indoors, where a main removal mechanism is deposition to surfaces. Deposition can be affected by the use of forced-air circulation through ducts or by air filters. In this study, we calculate the deposition rates of particles in an occupied house due to forced-air circulation and the use of in-duct filters such as electrostatic precipitators (ESP) and fibrous mechanical filters (MECH). Deposition rates are calculated for 128 size categories ranging from 0.01 to 2.5 μm. More than 110 separate "events" (mostly cooking, candle burning, and pouring kitty litter) were used to calculate deposition rates for four conditions: fan off, fan on, MECH installed, ESP installed. For all cases, deposition rates varied in a "U"-shaped distribution with the minimum occurring near 0.1 μm, as predicted by theory. The use of the central fan with no filter or with a standard furnace filter increased deposition rates by amounts on the order of 0.1–0.5 h^{-1}. The MECH increased deposition rates by up to 2 h^{-1} for ultrafine and fine particles but was ineffective for particles in the 0.1–0.5 μm range. The ESP increased deposition rates by 2–3 h^{-1} and was effective for all sizes. However, the ESP lost efficiency after several weeks and needed regular cleaning to maintain its effectiveness. A reduction of particle levels by 50% or more could be achieved by use of the ESP when operating properly. Since the use of fans and filters reduces particle concentrations from both indoor and outdoor sources, it is more effective than the alternative approach of reducing ventilation by closing windows or insulating homes more tightly. For persons at risk, use of an air filter may be an effective method of reducing exposure to particles.
Published by Elsevier Ltd.

Keywords: Ultrafine particles; Fine particles; Deposition; Filtration; Air cleaner; Field study

1. Introduction

The rate at which particles deposit on surfaces indoors is an important parameter in determining human exposure to airborne particles. The rate is a function of many factors, including particle size, surface characteristics, room surface-to-volume ratio, and room air flow. In many homes, central heating and air conditioning (HAC) systems circulate air through components (e.g., ducts, fan blades, furnace, heat exchanger, etc.) where additional opportunities for particle deposition occur. In addition, operation of the HAC system may enhance particle deposition to room surfaces due to increased air motion. Also, in some homes, the use of air filters, either portable or mounted in the ventilation duct, increases still further the deposition rate.

At least 24 previous studies of particle deposition have been carried out in homes, test houses, and controlled chambers. Lai (2002) has compiled data regarding 15 of these studies, 11 of which were completed in an experimental chamber. Additional chamber studies include Mosley et al. (2001) and Byrne et al. (1995).

*Corresponding author. Tel.: +1-703-620-4543; fax: +1-703-860-0678.

E-mail address: wallace.lance@epa.gov (L.A. Wallace).

1352-2310/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.atmosenv.2003.10.003

The remaining tests were conducted either in controlled test houses (Offermann et al., 1985; Xu et al., 1994; Emmerich and Nabinger, 2001; Thatcher et al., 2002) or in occupied or unoccupied houses (Thatcher and Layton, 1995; Wallace et al., 1997; Fogh et al., 1997; Abt et al., 2000; Long et al., 2001a; Vette et al., 2001; Howard-Reed et al., 2003). These studies have measured deposition rates for a full range of particle sizes, from ultrafines (<0.1 μm) to accumulation mode (0.1–1 μm) to fine particles (< 2.5 μm) and coarse particles (2.5–10 μm).

A number of studies have considered deposition in ducts from either a modeling or experimental point of view. Sippola and Nazaroff (2002) presented both an Eulerian and an empirical model of deposition in straight and curved ducts, concluding that most deposition is by gravitational settling to floors of ducts and impacts at bends. Few studies, however, have investigated the effects of central heating and air conditioning on particle deposition, and fewer still have looked at the effect of in-duct mechanical or electrostatic filters (Hanley et al., 1994; Fugler and Bowser, 2002.). Recently, Howard-Reed et al. (2003) published a study of the effects of central fans and electrostatic precipitators on particle deposition rates for particles in the fine and coarse range (0.3–10 μm) as measured by optical particle counters with six broad size ranges. This study extends Howard-Reed's approach to ultrafine particles (0.01–0.1 μm) and to fine particles (0.54–2.5 μm) using finer size classifications (128 size ranges).

2. Methods and materials

All measurements were made over a 2-year period (July 1999–June 2001) in an occupied town house. The town house has been described fully in previous publications (Wallace et al., 2002; Wallace and Howard-Reed, 2002). Briefly, it is a four-bedroom house of three stories (basement, first floor, and second floor) with a volume of about 400 m^3. The furnace is operated by natural gas; the air conditioner by electricity. A central fan circulates heated, air-conditioned, or untreated air through ductwork entirely contained in the conditioned area. The forced-air system uses 100% recirculated air. During the experimental period, the house was occupied by two nonsmoking adults.

Two main particle-monitoring instruments were located in the basement throughout the study. The first of these was a Scanning Mobility Particle Sizer (SMPS) consisting of a differential mobility analyzer (DMA) (Model 3071, TSI, Inc., St. Paul, MN) linked to a condensation particle counter (CPC) (Model 3010, TSI Inc., St. Paul, MN) (Agarwal and Sem, 1980). Two nozzles were used alternately for about a month at a time. The smaller nozzle spanned a range of particle sizes between 10 and 450 nm in diameter. The larger nozzle covered a range of 18–1000 nm. Each system included about 100 distinct particle sizes. The SMPS requires a minimum scan time of about 2.5 min; a sampling period of 5 min was selected for this study. A ratio of 10:1 for sheath air flow to sample air flow was adopted for each inlet. Flow rates were 0.36 $m^3 h^{-1}$ (6 l min^{-1}) and 0.036 $m^3 h^{-1}$ (0.6 l min^{-1}) for the smaller inlet and 0.12 $m^3 h^{-1}$ (2 l min^{-1}) and 0.012 $m^3 h^{-1}$ (0.2 l min^{-1}) for the larger inlet. Voltage settings for the two internal flow meters were checked each time the instrument was downloaded (at least every 3 days). The voltage settings were required to be within 0.1% of the recommended value in the manual. A bubble flowmeter was used to set the sample flow for the single external flow meter to within 0.3% of the recommended flow. When the pressure drop exceeded 550 kPa (80 psi), the smaller inlet was removed and soaked in isopropanol and cleaned with compressed air. The larger inlet was then used for a period of about a month before beginning the cycle again with the smaller inlet. The SMPS is considered a reference instrument for determining sizes of particles to within 3% (Kinney et al., 1991) but not necessarily the concentrations. Since only one SMPS was used, no measurements of precision were made.

The second instrument was an Aerodynamic Particle Sizer (APS) (Model 3320, TSI Inc., St. Paul MN). This instrument accelerates particles between two lasers, thus determining aerodynamic diameter directly for particles in 50 size categories between 0.54 and 20 μm. Like the SMPS, the APS returns a particle number concentration as the primary unit. An averaging period of 1 min was selected for this study. The pump flow was checked periodically with the bubble flowmeter. The internal and external inlets were also removed and cleaned periodically. The exhaust port was vacuumed when warranted. This APS model has been found to be undependable for particles larger than about 5 μm due to entraining smaller particles into the larger size classifications (Armendariz and Leith, 2000). For that reason, no results are reported here for particles >5 μm. The additional observation by Armendariz and Leith (2000) that the concentrations in the smallest size categories measured by the APS were biased low was considered not to affect our calculations of deposition rates. Since only one APS was used in this study, no measurements of precision were made. The manufacturer's estimate of the accuracy of the instrument is ±10%.

The house's air change rate was measured using the tracer decay method as described in ASTM Standard E741 (ASTM, 2001) with sulfur hexafluoride (SF_6) as the tracer gas and a gas chromatograph with electron capture detector (GC-ECD) detection system. Every 2 or 4 h a tracer gas (SF_6) was injected into the return duct. Tubes sampled the gas sequentially every minute in the return air duct and in 9 rooms of the house including the attic. The GC-ECD was calibrated using an 18-point calibration system to measure SF_6 concentrations between $30\,\mu g\,m^{-3}$ (5 ppb(v)) and $900\,\mu g\,m^{-3}$ (150 ppb(v)) with an accuracy of approximately $\pm 2\%$. Air change rates were calculated regressing the logarithm of the tracer gas concentration against time. Since with the central fan on it takes about 30 min for all rooms to achieve equilibrium tracer gas concentrations after an initial injection into the return duct, the regression was carried out from 30 min past the hour until 30 min past the next hour. Although errors from these instruments are relatively small, those that are multiplicative in nature, such as flow rates, will not affect the estimates of air change rates, since those depend on regressions on the logarithms of the rates.

Temperature was measured sequentially every 5 min in 10 indoor locations (same locations as SF_6 samples) and outdoors with thermistors (accuracy of $\pm 0.4°C$). Relative humidity (RH) was measured every 5 min in five indoor locations including the attic, and outdoors using bulk polymer resistance sensors with an accuracy of $\pm 3\%$ RH. Since the attic fan came on automatically when attic temperatures reached a certain point, the times it turned on or off were recorded electronically and transmitted to a computer.

The supply air flow rate through the HAC system was measured by performing a velocity traverse conducted in the supply air duct with a hot wire anemometer (HWA) to find a point representative of the average velocity in the return duct. An HWA was then mounted at that point to monitor duct air flow velocity during the experiments. The HWA has an uncertainty of 2.5% of the indicated reading. The measurements were performed in accordance with ASHRAE Standard 111 (ASHRAE, 1988), which is estimated to result in an uncertainty of 5–10% under field conditions. The traverse test on the system supply was repeated several times, and a similar traverse was performed on the system return to better characterize the system flows. The average supply flow was 530 l/s and the average return flow was 675 l/s. While the HAC system was operating in fan constant mode, a balometer with an estimated accuracy of 10% was used to measure the individual HAC system supply flows. After accounting for unmeasurable flows the sum of measured supplies agreed reasonably well with the results of the traverse test. A system duct leakage test confirmed the presence of significant supply and return leakage. Using the average of the measured supply and return air flow rates, the duct velocity was converted to an air flow rate of approximately $5.4\,h^{-1}$, with an estimated uncertainty of about 20%, when the central fan was operating.

Two types of in-duct filters were tested: an ESP and a MECH. The ESP positively charges particles with ionizing wires at 6200 V. The charged particles are then removed by grounded collector plates. The ESP required frequent cleaning to maintain high removal efficiencies. The MECH has an extended surface area with a thickness of 0.13 m. The manufacturers' stated average arrestance was 93% per ASHRAE Standard 52.1 (ASHRAE, 1992). Duct velocities appeared to be unaffected by the presence or absence of a filter. For example, after 1600 h of operation of the MECH, the best-fit regression line had changed from 4.65 to $4.68\,m\,s^{-1}$ ($N = 19,200$, slope $= 2 \times 10^{-5}$, $R^2 = 0.008$). After 2700 h of operation of the ESP, the average velocity went from 4.80 to $4.76\,m\,s^{-1}$ ($N = 32,400$, slope $= -1 \times 10^{-5}$, $R^2 = 0.028$). With no in-duct filter operating, the average velocity over 10 days was $4.88\,m\,s^{-1}$.

Each type of filter was installed at different times in the return duct. Probes were placed in the duct upstream and downstream from the filter. Optical particle counters (OPC) (Model 500-I, Climet Instruments, Inc., Redlands, CA) were attached to the probes to determine the single-pass efficiency of the filters for fine and coarse particles. (No measure of efficiency was attempted for ultrafine particles.) This optical scattering instrument provided six size ranges from 0.3 to $>10\,\mu m$. The size ranges chosen for this study were 0.3–0.5, 0.5–1, 1–2.5, 2.5–5, 5–10, and $>10\,\mu m$. A low-flow $0.17\,m^3/h$ (0.1 cfm) pump was chosen to allow a higher saturation concentration of 300 particles cm^{-3} (10^7 particles per cubic foot) than is possible on the standard $1.7\,m^3\,h^{-1}$ (1 cfm) instrument. A 1-min integrating period at 5-min intervals was chosen for this instrument. The upstream and downstream OPCs were run for several hours side-by-side, sampling from the same atmosphere, to establish the relative bias of each of the size categories. Then the instruments were corrected for bias when establishing the efficiency of the filters. The precision of the OPC varies according to the size range considered, with the best precision at the smallest size ranges (which have the largest number of particles). Measured average precision following correction for bias was $<3\%$ for the 0.3–0.5 μm size category, $<5\%$ for the 0.5–1 μm category, and $<10\%$ for the 1–2.5 μm category.

Three main particle sources were employed. Cooking took place in the kitchen. A citronella candle was burned for 1 or 2 min, usually in the utility room in the basement but sometimes upstairs. Kitty litter was poured at intermittent times, always in the basement. A fourth "source"—outdoor air—was sometimes employed, by opening windows until equilibrium had been achieved and then closing the windows and turning on the central fan and in-duct filter to achieve a new lower equilibrium with outdoor air.

To measure particle decay in a multizone house, it is important to achieve good mixing throughout the house. This was supplied by the central fan, which forced about five house volumes of air through the ducts every hour. To measure decay when the fan was off, it was necessary to keep the fan on for about half an hour after one of the particle source activities ended to ensure mixing throughout the house, and then to turn the fan off to measure the decay. This approach was not adequate for coarse particles, however, since they settle out faster than they can be mixed throughout the house. Therefore, a procedure was adopted in which the basement was entirely closed off, using towels stuffed under the door at the top of the basement stairs. Instruments placed outside the basement confirmed that particles were not escaping in significant numbers. This procedure was followed for the two sources located in the basement (candle and kitty litter).

The approach to measuring particle decay was as follows: for any of the three main sources, if a sufficiently large peak occurred allowing an extended decay period, the decay of the particles was estimated using linear regression on the logs of either the number or volume concentration (Fig. 1). The negative slope (in units of inverse hours) is the total decay rate, from which the air change rate can be subtracted to provide the deposition rate. For each particle size category, the regression was required to have an R^2 value >0.9 to be acceptable. When the fan is off, the measured deposition rate is the natural particle deposition rate. When the fan is on but no in-duct filter is operating, the measured deposition rate is the natural particle deposition rate plus the rate due to deposition in the HAC system (and possibly increased turbulence due to increased air velocity). And when the fan is on and the in-duct filter is working, the measured particle deposition rate includes the natural rate, the rate due to air flow through the HAC system, and the rate due to deposition on the filter. Thus there are three cases (fan off, fan on but no filter, fan on with filter) to be differentiated.

An important aspect of measuring the slope of the decay is the proper subtraction of the background. The best results occur when the background levels of all particle size categories are the same just before and after the peak. This is evidence that, for example, the outdoor air concentration, which was usually unmeasured, has remained fairly constant. Fortunately, since most of the calculations of decay rates covered a half hour or less, even a fairly rapid change in outdoor concentrations would produce little change in the indoor values over this small time period.

A computerized database was created for the 18-month period from 1 July 1999 to 31 December 2000. Known as PMHOME, it consists of several Statistica (Version 6.0, Statsoft, Tulsa, OK) files containing the number and volume concentrations measured by the SMPS and APS, the air change rate data, the electronic records of the times when the central and attic fans were operating, and the temperature and RH values from the various rooms in the house. All data are at 5-min resolution, providing a possible 105,408 cases for the year 2000 (a Leap Year). The entire database was manually searched for sharp peaks indicating indoor sources. These peaks and the ensuing period of increased concentrations were tagged as indoor source events. Since different sources result in elevating different particle sizes, this search was repeated for each of four widely separated particle sizes: 0.02, 0.2, 0.7, and 2 μm. The resulting set of four variables allows times with no indoor source to be separated from times when an indoor source is either operating or has left an

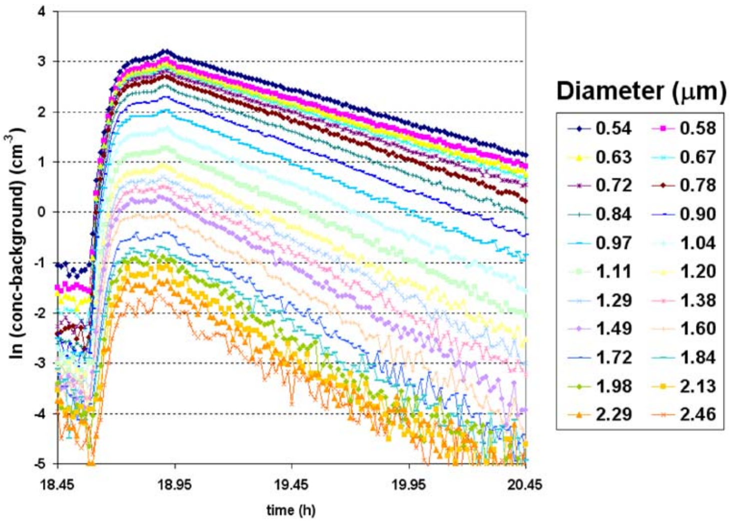

Fig. 1. Decay of fine particles (<2.5 μm) in basement as measured by APS after cooking tortillas in kitchen. Successive points are 1 min apart.

elevated concentration above background. During the year 2000, increased concentrations due to indoor sources were apparent 22%, 7%, 14%, and 16% of the time for the four particle sizes, respectively.

3. Results

About 4640 hourly air change values were obtained during 2000. The mean (SD) air change rate was 0.64 (0.56) h^{-1}. Most of these measurements (3460) had relative standard deviations (RSD) <15% over all eight of the conditioned rooms.

The efficiency of the ESP varied considerably depending on the time since the last cleaning of the wires and plates (Fig. 2). Efficiencies exceeded 90% for fine particles and 99% for coarse particles soon after cleaning, but began dropping below 90% after several hundred hours of operation for the fine particles and after a few hundred hours more for the coarse particles. We believe that these efficiencies are not much affected by leakage or bypass around the filter, since efficiencies for the coarse particles were 99% for many hours after cleaning. By contrast, the efficiency of the MECH filter remained near zero for fine particles (Fig. 3). For coarse particles, the efficiency increased as the filter dustcake built up. A more detailed discussion of the efficiencies of these filters is found in Emmerich and Nabinger (2001).

For the SMPS, a total of 70 events were selected for analysis, divided among the three main conditions as follows: 11 with the fan off, 41 with the fan on but no filter, and 18 with the fan on and a filter, either the MECH or the ESP, installed in the return duct and operating. For the APS, the corresponding values were 43 (total), 20, 11, and 12. The estimated mean and standard deviations of the deposition rates for each

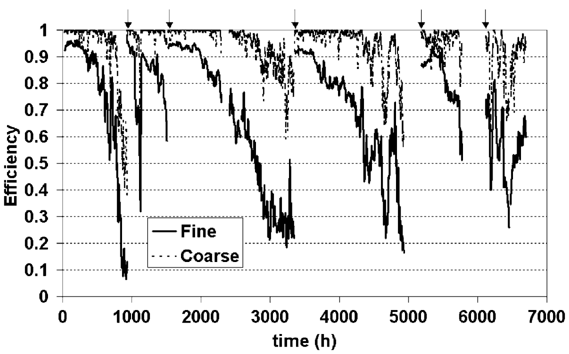

Fig. 2. Volume-weighted 12-h average single-pass efficiency of ESP for fine particles (between 0.3 and 2.5 μm) and coarse particles (2.5–10 μm) as a function of time since cleaning. Arrows mark five cleaning episodes that occurred during the 9 months of testing.

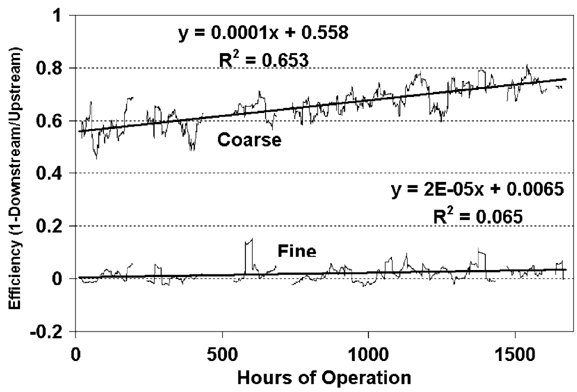

Fig. 3. Volume-weighted 12-h average single-pass efficiency of mechanical filter (MECH) for fine (0.3–2.5 μm) and coarse (2.5–10 μm) particles. The filter was not cleaned over the 2 months of operation.

condition, averaged over 5 adjacent particle sizes, are provided in Table 1.

The deposition rates were generally lowest when the central fan was off and highest when the ESP filter was operating (Figs. 4 and 5). For most particle sizes, the rates increased slightly when the fan was turned on, even if no filter was installed or working. The MECH increased the apparent deposition rate compared to no filter at all, but was not as effective as the ESP, except possibly for the smallest of the ultrafine particles.

4. Discussion

The shape of the curves in Fig. 5 is roughly as predicted by theory (Lai and Nazaroff, 2000). Deposition rates are high (>3 h^{-1}) for the smallest particles due to diffusion and for the largest particles due to gravitational settling. A minimum rate between 0.1 and 0.3 μm, depending largely on the average velocity of indoor air, is predicted by theory (Lai and Nazaroff, 2000) and is consistent with the observed minimums at about 0.11–0.13 μm. However, the measured deposition rates for the case with the fan off are about an order of magnitude higher than predicted by theory for smooth surfaces. Since much of the basement was carpeted, and other floors included a number of rugs, deposition rates would be expected to be higher than predicted for smooth surfaces, but this seems unlikely to account for an order of magnitude increase. Also, this effect would be reduced for the largest particles, for which gravitational settling is dominant.

The varying efficiencies determined for the filters contribute to the uncertainties associated with estimates of the deposition rate when the filters are nominally working. For example, even if the ESP was noted as being on, its efficiency for fine particles could take on

Table 1
Mean deposition rates for fan off, fan on, mechanical filter (MECH) and electrostatic precipitator (ESP)

Diam. (μm)	Mean values[a] (h^{-1})				Standard deviations (h^{-1})				Number of events			
	ESP	MECH	Fan	No fan	ESP	MECH	Fan	No fan	ESP	MECH	Fan	No fan
0.0106			3.92				1.86				26	
0.0126			3.54	4.10			1.92	2.03			27	4
0.0151			3.02	3.68			1.72	2.10			31	5
0.0181	4.77	4.53	2.74	3.08	1.77	0.90	1.46	1.68	7	7	34	5
0.0217	4.40	4.26	2.54	2.54	1.32	0.82	1.28	1.14	7	7	37	6
0.0259	3.96	3.56	2.30	2.00	0.96	0.42	1.04	1.00	7	8	36	7
0.0311	3.58	3.00	2.08	1.66	0.78	0.30	0.80	1.04	7	8	33	9
0.0372	3.30	2.46	1.88	1.54	1.00	0.30	0.64	1.04	7	8	31	10
0.0445	3.02	2.04	1.64	1.26	1.00	0.30	0.60	0.84	7	8	31	11
0.0533	3.08	1.68	1.42	1.00	1.36	0.20	0.52	0.72	8	8	29	11
0.0638	2.88	1.38	1.24	0.96	1.18	0.20	0.50	0.80	8	8	27	10
0.0764	2.72	1.14	1.12	0.86	1.08	0.20	0.54	0.68	8	8	25	10
0.0914	2.66	1.00	1.00	0.80	0.96	0.20	0.58	0.60	8	8	22	9
0.1094	2.74	0.90	0.92	0.70	1.00	0.24	0.58	0.50	8	8	20	9
0.1310	2.72	0.96	0.90	0.72	1.06	0.32	0.64	0.50	8	8	20	9
0.1568	2.70	1.00	0.94	0.78	1.10	0.38	0.72	0.52	8	8	18	9
0.1877	2.66	1.06	1.08	0.80	1.34	0.32	0.78	0.60	8	8	16	9
0.2247	2.72	1.10	1.18	0.92	1.52	0.40	0.80	0.68	6	8	16	8
0.2690	2.62	1.02	1.24	0.98	1.72	0.34	0.78	0.72	6	7	15	7
0.3220	2.68	1.00	1.28	0.94	1.88	0.34	0.94	0.68	6	4	15	6
0.3854	2.48	0.92	1.20	0.96	1.68	0.28	0.62	0.42	5	3	8	3
0.6260	3.42	1.66	0.96	0.80	0.63	0.83	0.40	0.43	12	7	11	8
0.8980	4.34	2.10	1.34	1.04	0.90	0.90	0.46	0.56	9	7	11	16
1.286	5.30	2.94	1.90	1.36	1.48	0.98	0.58	0.52	3	6	10	20
1.843	5.65	4.18	2.60	1.80	1.14	1.26	0.62	0.50	2	5	8	19
2.642		4.6	4.22	2.44		1.65	1.20	0.60		3	3	16
3.786				3.72				0.60				12
5.425				5.32				0.68				11

[a] Values averaged over five adjacent particle sizes centered at diameter shown.

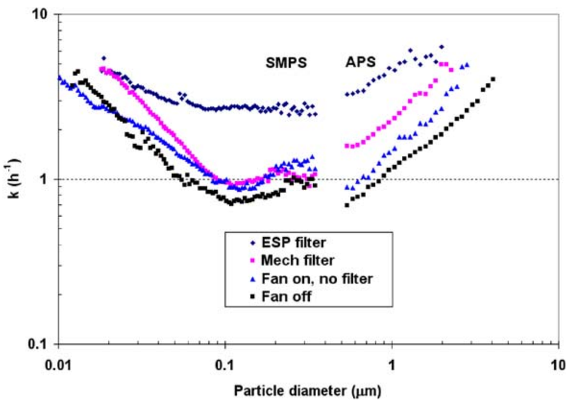

Fig. 4. Deposition rates by particle size.

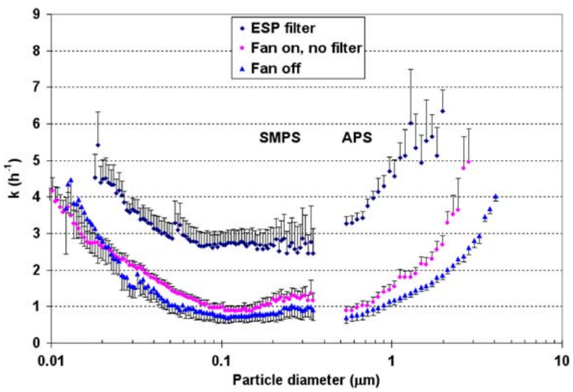

Fig. 5. Deposition rates with error bars showing either +1 SE or −1 SE (only three of four cases shown for clarity).

any value between 10% and 95% depending on the time since the last cleaning. This suggests that our estimate of the effect of the ESP is an underestimate of the effect of a perfectly clean filter. However, as a practical matter, our estimate may be close to the effect of an ESP filter under normal use with intermittent cleaning.

The MECH was associated with lower deposition rates than the ESP for nearly all particle sizes, consistent with the measured efficiencies for fine particles using the OPCs. However, the MECH appeared to approach the effect of the ESP at the smallest ultrafine diameters, perhaps due to increased ability to intercept a particle when its Brownian motion is high, and at the highest (supermicrometer) diameters. The efficiency of the MECH for coarse particles (2.5–10 μm) approached 80% after 1500 h of use.

Our finding that the use of a central fan without a filter affects fine particle deposition rates (as measured by the SMPS and APS) is in agreement with the earlier finding of Howard-Reed et al. (2003) using different instruments (OPCs). For the three smallest size fractions measured by the OPC (0.3–0.5, 0.5–1, and 1–2.5 μm) Howard-Reed et al. found that having the fan on led to increases in the deposition rate of 0.47, 0.50, and 0.72 h^{-1}, respectively. Corresponding values for our SMPS and APS measurements, averaging by volume across the many size categories contributing to the same size fractions, were 0.23, 0.22, and 0.75 h^{-1}, respectively. The additional increases in deposition rates due to the ESP filter were found by Howard-Reed et al. to be 2.1, 2.8, and 2.4 h^{-1} for the same three size fractions, compared to our values of 2.3, 2.8, and 3.0 h^{-1}, respectively.

We now estimate the effects of these deposition rates on particle concentrations in a residence, using the mean deposition rates for each size category. We assume no indoor sources are operating, with the resultant time-averaged mass balance model $C_{in} = PaC_{out}/(a+k)$. Here P is the penetration factor, which we will take as unity (Özkaynak et al., 1996), and k is the observed deposition rate for the given ventilation condition. We take the mean air change rate of 0.64 h^{-1} observed over the year 2000 in this house (Wallace et al., 2002) as a "typical" air change rate, and select values of 0.2 and 1.2 h^{-1} to represent "tight" and "drafty" homes, respectively. We calculate an outdoor number distribution of particles based on the mean indoor number concentrations at times with no indoor sources from one year of observations in an occupied townhouse (Wallace and Howard-Reed, 2002). During the year chosen (2000), the MECH was not used and the ESP, although used briefly at the end of the year, was experiencing failures of the power supply and was probably not effective. Since the central fan was on 89% of the time in that year, we calculate the outdoor concentrations using the observed values of k for the case with the central fan on (Fig. 6). The resulting volume concentration of the computed outdoor distribution (integrated from 0.01 to 2.5 μm) is 16.3 $(\mu m/cm)^3$. For the "typical" air change rate of 0.64 h^{-1}, and no fan or filter, these choices result in a calculated volume fraction of outdoor particles remaining airborne indoors of 0.47; the equivalent number fraction is 0.28. (The number fraction is smaller than the volume or mass fraction since most of the particles are ultrafine particles with greater deposition rates.) For this case, use of the central fan alone was calculated to reduce the number-weighted particle load by 14%, whereas the MECH would reduce the particles by 23% and the ESP by 51% (Table 2). These reductions are somewhat greater in the tight house and somewhat less in the drafty house, although even in the latter the ESP is estimated to reduce the concentrations by 44%. These estimates of a 44–59% reduction in particle concentrations produced by the ESP are consistent with the finding by Fugler and Bowser (2002) that an in-duct ESP reduced particle levels in five homes by 30–70%, depending on resident activity level. Riley et al. (2002) completed an extensive modeling exercise. For an urban residential model scenario with a central fan always operating (equivalent air flow rate of 4 h^{-1}, compared to our rate of 5 h^{-1}) and furnace filter present, and assuming an air change rate of 0.75 h^{-1}, their model

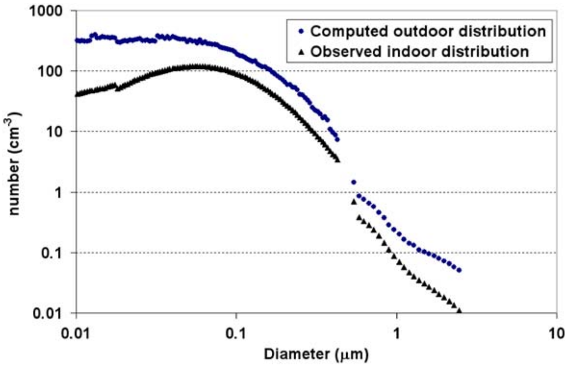

Fig. 6. Computed outdoor distribution of particles based on observed indoor distribution over the year 2000 ($N = 45{,}000$ measurements), using the calculated size-specific deposition rates for the fan-on no-filter condition.

Table 2
Calculated fractions (f) of outdoor air particles remaining indoors if no fan or filter is used, and additional reductions (%) in particle concentrations due to use of an electrostatic precipitator (ESP), mechanical (fibrous) air filter (MECH), and central fan alone for a house with low, medium or high air exchange rates

AER[a]	f	ESP	MECH	Fan
Number-weighted				
0.2	0.12	59	28	18
0.64	0.28	51	23	14
1.2	0.39	44	20	11
Volume-weighted				
0.2	0.20	65	19	20
0.64	0.47	57	16	16
1.2	0.65	51	14	13

[a] Air exchange rate (h^{-1}).

predicted an indoor volume (number) fraction of the outdoor air concentration of about 0.46 (0.27). Using their choice of $0.75\,h^{-1}$ for an air change rate we arrive at similar values of 0.44 (0.26).

Although the calculations above ignore indoor sources of particles, use of the central fan and filter will also reduce exposures to such particles, since they will decay more rapidly. However, a quantitative calculation of the effect is difficult, since it depends partially on the proximity of the person to the source, and the rapidly varying nature of particle concentrations produced by indoor sources make use of the time-averaged mass balance model inappropriate.

These findings suggest that for persons susceptible to illness exacerbated by high particle levels, use of a central fan and in-duct filter can appreciably lower their exposures during times of high outdoor particle concentrations. This is preferred to the alternative approach of reducing the air change rate (e.g., by closing windows or insulating the house more tightly), which will reduce exposure to particles generated outdoors but will actually increase exposure to particles generated indoors. Since at least one study suggests that indoor particles are equally as toxic as outdoor particles (Long et al., 2001b), it appears desirable to reduce exposure to particles from both sources, which can be brought about by use of the central fan and high-efficiency in-duct filter but not by reducing the air change rate.

5. Conclusions

This study confirms and extends the findings of Howard-Reed et al. that (1) use of a central forced-air fan can by itself reduce particle levels in a home and (2) use of an in-duct filter can reduce these levels still further. The ESP was shown to be more effective than the MECH, particularly for fine particles, although attention needs to be paid to proper cleaning frequency. This study presents some of the first measurements of deposition rates for ultrafine particles as a function of use of the central fan and various filters. These rates can be quite high, particularly for the smallest ultrafine particles. The very strong effect of the ESP, and to a lesser degree, of the MECH, on particle decay rates suggests that use of these or other high-efficiency filters (with proper maintenance) could provide a dramatic lowering of indoor particle concentrations, whether the particle source is indoors or outdoors.

Acknowledgements

We acknowledge the contributions of Stuart Dols and Steven Nabinger of the National Institute of Standards and Technology in constructing, calibrating, and repairing the equipment. The perceptive remarks of an anonymous reviewer helped to improve this report.

Disclaimer

This study was partially funded by an EPA Internal Grant to the first author. It has been reviewed and cleared for publication. Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

References

Abt, E., Suh, H.H., Catalano, P., Koutrakis, P., 2000. Relative contribution of outdoor and indoor particle sources to indoor concentrations. Environmental Science and Technology 34, 3579–3587.

Agarwal, J.K., Sem, G., 1980. Continuous flow single-particle-counting condensation nucleus counter. Journal of Aerosol Science 11, 343–352.

Armendariz, A., Leith, D., 2000. Concentration measurement and counting efficiency for the aerodynamic particle sizer 3320. Journal of Aerosol Science 33, 133–148.

ASHRAE, 1988. Standard 111–1988. Practices for Measurement, Testing, Adjusting and Balancing of Building Heating, Ventilation, Air-Conditioning and Refrigeration Systems. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE, 1992. Standard 52.1, Gravimetric and Dust Spot Procedures for Testing Air Cleaning Devices Used in General Ventilation for Removing Particulate Matter. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

ASTM, 2001. Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution. E741-00. American Society for Testing and Materials International, West Conshohocken, Pennsylvania.

Byrne, M.A., Goddard, A.J.H., Lange, C., Roed, J., 1995. Stable tracer aerosol deposition measurements in a test chamber. Journal of Aerosol Science 26, 645–653.

Emmerich, S.J., Nabinger, S.J., 2001. Measurement and simulation of the IAQ impact of particle air cleaners in a single zone building. Journal of Heating,Ventilation, Air-Conditioning and Refrigeration Research 7, 223–244.

Fogh, C.L., Byrne, M.A., Roed, J., Goddard, A.J.H., 1997. Size specific indoor aerosol deposition measurements and derived I/O concentrations ratios. Atmospheric Environment 31, 2193–2203.

Fugler, D., Bowser, D., 2002. Reducing particulate levels in houses. In: Levin, H. (Ed.), Indoor Air 2002: Proceedings of the Ninth International Conference on Indoor Air Quality and Climate, Monterey, CA, Vol. 1, June 30–July 5, 2002, pp. 868–873; Indoor Air 2002, Santa Cruz, CA.

Hanley, J.T., Ensor, D.S., Smith, D.D., Sparks, L.E., 1994. Fractional aerosol filtration efficiency of in-duct ventilation air cleaners. Indoor Air 4, 169–178.

Howard-Reed, C., Wallace, L., Emmerich, S., 2003. Effect of ventilation systems and air filters on decay rates of particles produced by indoor sources in an occupied townhouse. Atmospheric Environment 37, 5295–5306.

Kinney, P.D., Pui, G.Y.H., Mulholland, G.W., Bryner, N.P., 1991. Use of the electrical classification method to size 0.1 μm SRM particles—a feasibility study. Journal of Research of the National Institute of Standards and Technology 96, 147–1176.

Lai, A.C.K., 2002. Particle deposition indoors: a review. Indoor Air 12, 211–214.

Lai, A.C.K., Nazaroff, W.W., 2000. Modeling indoor particle deposition from turbulent flow onto smooth surfaces. Journal of Aerosol Science 31, 463–476.

Long, C.M., Suh, H.H., Catalano, P., Koutrakis, P., 2001a. Using time- and size-resolved particulate data to quantify indoor penetration and deposition behavior. Environmental Science and Technology 35, 2089–2099.

Long, C.M., Suh, H.H., Kobzick, L., Catalan, P.J., Ning, Y.Y., Koutrakis, P., 2001b. A pilot investigation of the relative toxicity of indoor and outdoor fine particles: in vitro effects of endotoxin and other particulate properties. Environmental Health Perspectives 109 (10), 1019–1026.

Mosley, R.B., Greenwell, D.J., Sparks, L.E., Guo, Z., Tucker, W.G., Fortman, R., Whitfield, C., 2001. Penetration of ambient fine particles into the indoor environment. Aerosol Science and Technology 34, 127–136.

Offermann, F.J., Sextro, R.G., Fisk, W.J., Grimsrud, D.T., Nazaroff, W.W., Nero, A.V., Revzan, K.L., Yater, J., 1985. Control of respirable particles in indoor air with portable air cleaners. Atmospheric Environment 19, 1761–1771.

Özkaynak, H., Xue, J., Weker, R., Butler, D., Koutrakis, P., Spengler, J., 1996. The Particle TEAM (PTEAM) Study: Analysis of the Data, Vol. 3. Research Triangle Park, NC, 1996. EPA/600/R-95/098.

Riley, W.J., McKone, T.E., Lai, A.C.K., Nazaroff, W.W., 2002. Indoor particulate matter of outdoor origin: importance of size-dependent removal mechanisms. Environmental Science and Technology 36, 200–207.

Sippola, M.R., Nazaroff, W.W., 2002. Modeling particle deposition in ventilation ducts. In: Levin, H., (Ed.), Indoor Air 2002: Proceedings of the Ninth International Conference on Indoor Air Quality and Climate, Monterey, CA, Vol. 1, 30 June–5 July 2002, pp. 515–520; Indoor Air 2002, Santa Cruz, CA.

Thatcher, T.L., Layton, D.W., 1995. Deposition, resuspension, and penetration of particles within a residence. Atmospheric Environment 29, 1487–1497.

Thatcher, T.L., Lai, A.C.K., Moreno-Jackson, M., Sextro, R.G., Nazaroff, W.W., 2002. Effects of room furnishings and air speed on particle deposition rates indoors. Atmospheric Environment 36, 1811–1819.

Vette, A.F., Rea, A.W., Lawless, P.A., Rodes, C.E., Evans, G., Highsmith, V.R., Sheldon, L., 2001. Characterization of indoor–outdoor aerosol concentration relationships during the Fresno PM exposure studies. Aerosol Science and Technology 34, 118–126.

Wallace, L., Howard-Reed, C., 2002. Continuous monitoring of ultrafine, fine, and coarse particles in a residence for 18 months in 1999–2000. Journal of the Air and Waste Management Association 52, 828–844.

Wallace, L.A., Quackenboss, J., Rodes, C., 1997. Continuous measurements of particles, PAH, and CO in an occupied townhouse in Reston, VA. In: Measurement of Toxic and Related Air Pollutants, Proceedings of EPA-AWMA Symposium on Toxic and Related Compounds. Research Triangle Park, NC, 29 April–1 May 1997, pp. 860–871; Air and Waste Management Association, Pittsburgh, PA. VIP-74.

Wallace, L., Emmerich, S.J., Howard-Reed, C., 2002. Continuous measurements of air change rates in an occupied house for 1 year: the effect of temperature, wind, fans, and windows. Journal of Exposure Analysis and Environmental Epidemiology 12, 296–306.

Xu, M., Nematollahi, M., Sextro, R.G., Gadgil, A.J., 1994. Deposition of tobacco smoke particles in a low ventilation room. Aerosol Science and Technology 20, 194–206.